

The impact of human-biometeorological factors on perceived thermal comfort in urban public places

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Abstract

For the understanding of the impact of meteorological stressors on human perceptions of thermal comfort, it is essential to examine in detail the joint variability of atmospheric conditions and human perception. We designed an interdisciplinary experimental setup to generate data of both human-biometeorological and individual human perception at two different urban public places in the city of Aachen, Germany. Meteorological measurements at the human-biometeorological standard height of 1.1 m a.g.l. were taken during typical winter weather situations as well as extreme summer weather situations to analyze potentially seasonal effects. Pedestrians and tourists at the study site were selected as participants for face-to-face questionnaire-based interviews. We took measurements and held interviews between 10:00 h and 17:00 h (CEST/CET) to record the daytime agreement/deviations at different inner urban measurement locations. Based on an overall physical approach of thermal load, UTCI (Universal Thermal Climate Index) values are calculated. A maximum of +34.1 °C for summertime and a minimum of +2.6 °C for wintertime could be found. The meteorological parameters of air temperature (T_a), mean radiant temperature (T_{mrt}) and vapor pressure (VP) are compared with data perceived by the persons interviewed. In winter, T_a shows a significant relation to the overall weather perception ($r = 0.28$; $p < 0.05$) while the overall comfort of the participants is significantly related to perceived solar heat ($r = 0.27$; $p < 0.5$) as well as to perceived T_a ($r = 0.4$; $p < 0.002$). Quite different resulting patterns occurred for the summer campaign. None of the physical variables significantly affected the weather perception. Only the perceived T_a revealed a significant relation to the overall weather perception ($r = 0.27$; $p < 0.002$).

Keywords: thermal stress, urban public spaces, urban climate, field study, psychophysics measurements, thermal comfort

1 Introduction

Due to the consequences of urbanization and climate change, urban heat will become more severe in the next decades (SETO et al., 2011; BALLESTER et al., 2010). Various factors cause higher temperatures in cities than in rural regions: dark surfaces with low albedo, which absorb and then reradiate heat; less vegetation with accompanying lower rates of evapotranspiration; and heat from industries, vehicles and other sources (OKE, 1982). As urban areas cover only a small fraction of the Earth's surface, they play only a minor role in the global increase in mean near-surface air temperature (PARKER, 2006). However, urban areas do play an important role for regional climate and the regional characteristics of global climate change. One of the major problems is the high vulnerability of cities. The warming trend over recent decades and the increasing number of heat waves in

Europe have already contributed to increased morbidity and mortality in many regions of the world (PATZ et al., 2005; FISCHER et al., 2012). During heat waves, the well-known effect of the urban heat island (UHI) is enhanced and this leads to even more extreme events (GABRIEL and ENDLICHER, 2010). As a result, most heat wave deaths occur in cities (KOVATS and HAJAT, 2008; STONE et al., 2010). Heat cramps, heat strokes and cardiovascular diseases are the most frequent negative health consequences (KOVATS and HAJAT, 2008). Besides negative health effects, other consequences are the negative effects on human perception of weather conditions as well as on human thermal comfort. However, both are not the only important issues during summer. Only few studies have discussed thermal comfort in different seasons (e.g. HWANG et al., 2011). Since an urban public place may be comfortable in summer but uncomfortable in winter, the thermal comfort of a location must be assessed in different seasons. More than half of the world's population already live in cities. Worldwide, this fraction will continue to increase in the future due to positive urbanization rates (UNITED NATIONS, 2012). Differences in the

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surface energy budget of urban areas may substantially alter and possibly increase climate change impacts on the local population (FISCHER et al., 2012).

Therefore, a closer look at these possible impacts on local populations is an important next step. Since human perception of high thermal load on urban public places largely depends on overall weather perception, these relationships must be understood in detail in order to gain insight into perception patterns of different user groups regarding more extreme situations. Besides that, the main question of the present study concerns the connection between physically measured thermal comfort and perceived thermal comfort in urban public spaces.

1.1 Human-biometeorological approach

During the last decades, interest in the assessment of outdoor thermal comfort has increased because of climate changes and the increased heat stress in cities (HONJO, 2009). The thermal load can significantly affect mood, behavior and cognition. Especially in urban public spaces, people are often directly exposed to weather conditions (KELLER et al., 2005; LIN, 2009). Human thermal comfort is the outcome of the energy balance between the human body surface and the environment (MCGREGOR, 2011). Furthermore, it is influenced by human physiology, psychology and behavior (URBAN and KYSELYÌ, 2014). To evaluate thermal comfort, more than 100 different indices have been established in the last 50 years to describe the heat exchange between the human body and its surrounding environment (BŁAŻEJCZYK et al., 2012). However, most of these indices have been generated for indoor conditions. Only a few are applicable for outdoor conditions and meet the requirements of modern human-biometeorology by using the human heat budget as a basis. The thermal comfort indices mostly used for outdoor conditions are the Predicted Mean Vote (PMV), Standard Effective Temperature (SET), Effective Temperature (ET), Perceived Temperature (PT), Physiologically Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) (JOHANSSON et al., 2014). PMV was originally developed for indoor thermal comfort and should not be applied nowadays for outdoor thermal comfort due to its simple approaches for the fluxes of the human heat budget. However, in the last decades, it was often used in scientific studies (e.g. THORSSON et al., 2004; HODDER and PARSONS, 2007). In this study, we have used the latest development of thermal comfort indices, the UTCI. Developed by scientists from 22 countries (18 European countries) in 2005, the UTCI sets a new international standard for a better comparison of thermal comfort (JENDRITZKY et al., 2012; URBAN and KYSELYÌ, 2014). It is described as an equivalent ambient temperature ($^{\circ}\text{C}$) of a reference environment providing the same physiological response of a reference person as the actual environment. UTCI requires the meteorological data of T_a , VP or RH and T_{mrt} at the human-biometeorological standard height of 1.1 m a.g.l. and

wind speed at 10 m a.g.l. (JENDRITZKY et al., 2012). The calculation of the physiological response to the meteorological input is based on a multi-node model of human thermoregulation (FIALA et al., 2001). Wind speed and body movement variations strongly influence clothing insulation, vapor resistance and the insulation of surface air layers and will therefore also influence physiological responses (BŁAŻEJCZYK et al., 2012).

In recent years, different studies have emphasized the need for a combined human-biometeorological and social approach for a holistic analysis of thermal comfort within urban public spaces (KLEMM et al., 2015; MARAS et al., 2013; LIN et al., 2010; THORSSON et al., 2007). The concurrent sampling of datasets both from human-biometeorological and psychophysics allows for better understanding and improved estimation of individual weather perception.

1.2 Effects of weather on human perception

The vulnerability of humans to thermal extremes has been broadly investigated (KUNKEL et al., 1999; FISCHER and VAN DE VLIERT, 2011; STATHOPOULOS et al., 2004). Nevertheless, it has been receiving increased attention in view of the impacts of climate warming and heat stress related to a high seasonal and annual variability (PATZ et al., 2005; KOVATS and HAJAT, 2008). Weather conditions have been found to considerably affect health perception and physical comfort (BASU and SAMET, 2002; KEATINGE et al., 2000), especially in combination with other stressors that prevail in urban environments, such as particulate matter (VENN et al., 2001; BURKART et al., 2013) and traffic noise. Meteorological stressors – especially under sustained exposure – may lead to severe health risks in combination with higher morbidity and mortality (LEE, 2015). In particular, the elderly have been found to be highly sensitive to adverse effects induced by urban meteorological stressors (HAINES and PATZ, 2004; HAINES et al., 2006) due to their frailness and their susceptibility to respiratory as well as to cardiovascular diseases (MICHELOZZI et al., 2009).

However, even though there is no doubt about the factual risk of urban meteorological stressors on human health and well-being, it is unclear whether measurements of environmental stressors match perceptions of these stressors. This raises the question as to whether pedestrians do have the ability to adequately sense the stressors accordingly. This is not only doubtful due to individual differences in health perception and awareness (WATSON, 1988), but also due to the inconspicuousness of stressors in the natural environment, so that meteorological risk factors might be hidden by daily activities (LACHMAN and WEAVER, 1998). Moreover, it is highly probable that within urban environments those single subliminal stressors might overlap with each other and show up in combinations where it is difficult, or even impossible, for them to be perceived adequately. This



Figure 1: Study site area “Elisenbrunnen” in the city of Aachen with measurement points A–D. Blue dot marks the permanent weather station.

shall be one of the main working hypotheses of the presented study. Although it is not the main theme of this work, it should be noted that a pedestrian’s health status (MAHDIEH ABKAR et al., 2010), as well as their age or gender, might be influential psychological factors that considerably modify the stress perception within urban environments (NIKOLOPOULOU et al., 2001).

2 Methods

2.1 Study site description

The selected study site is the city of Aachen, North Rhine-Westphalia, Germany near the border to Belgium and The Netherlands, and which covers an area of 160 km². The city has approximately 250,000 residents and is situated in a basin with differences in altitude of up to 285 m a.s.l. We chose the city of Aachen as the test environment in order to gain insights into average conditions that are comparable to other European regions with an oceanic warm, moderate climate and that are not characterized by extreme weather variability. The maritime climate is especially driven by Atlantic low-pressure systems which lead to a comparatively high annual mean T_a of 10.5 °C (HAVLIK, 2002). However, the number of summer days, hot days and extremely hot days is rising and the occurrence of tropical nights also shows a slightly increasing trend (BUTTSTÄDT and SCHNEIDER, 2014). Furthermore, BUTTSTÄDT and SCHNEIDER (2014) found that heat waves are likely to last longer and occur more often in the future, whereas their intensity is not expected

to change significantly. Based on regional climate projections, BUTTSTÄDT and SCHNEIDER (2014) project a mean temperature increase of 1.6 K in Aachen between the decades 1971–2000 and 2031–2060.

We chose the inner city green space “Elisenbrunnen” on the edge of the historic city center of Aachen for detailed investigations on combined stress situations in urban public places (see Fig. 1). The study site spans an area of about 2 ha and is enclosed by buildings generally 4–5 floors high. Located in the southeast of the investigation area is one of Aachen’s most frequented roads by public transport buses and taxis. There is a main bus stop located within the investigation area. By contrast, a pedestrian road faces the park in the northwest. The roads surrounding the study site are only partly accessible by motor vehicles due to traffic-calmed zones.

Five specific measurement points were selected within the investigation site based on characteristics like the proportion of vegetation cover and surface sealing, traffic volume, frequency of pedestrians, microclimate conditions and the building structure surrounding the study area.

In this study, we will focus on two of the mentioned five measurement points (B and F, see Fig. 1) that are characterized by different attributes. Location B (“Glaskubus”) is an intensively sealed place with only one deciduous tree in close proximity and located directly next to a highly trafficked area. In contrast, location F (“Münzbrunnen”) shows a high rate of vegetation cover (grassland and deciduous trees with a height of up to 20 m) as it is situated at the edge of the park in close proximity to a traffic-calmed zone (see Fig. 2).



Figure 2: Measurement locations F (“Münzbrunnen”, left) and B (“Glaskubus”, right) during the winter campaign 2014.

2.2 Human-biometeorological measurement

We collected meteorological data at the human-biometeorological standard height of 1.1 m a.g.l. (VDI, 2008; MAYER and HÖPPE, 1987) using a mobile measurement system at five measurement points at “Elisenbrunnen” from the late morning to the late afternoon in winter and summer 2014. The measurement campaigns took place in February and July 2014 and were prolonged to 2015. The mobile weather station consists of a multisensory Vaisala Weather Transmitter WXT520 for measuring air temperature (T_a) [°C], relative humidity (RH) [%], wind direction (wd) [degree], wind speed (ws) [m/s] and air pressure (p) [hPa] (see Fig. 3). The humidity values of vapor pressure (VP) [hPa] were calculated by using the Magnus formula.

Furthermore, three *Kipp & Zonen* net radiometers were used to generate data of 3-D infrared and solar radiation according to HÖPPE (1992) and comparative studies (LEE et al., 2014; MARAS et al., 2013; HOLST and MAYER, 2011; MAYER et al., 2008; ALI-TOUDERT and MAYER, 2007).

All devices of the mobile measurement system (Weather Transmitter WXT520 and net radiometer) worked with a sampling rate of 0.2 Hz (5 sec). Uncertainties of the Weather Transmitter WXT520 are ± 0.3 °C for T_a ; ± 3 % for RH ; ± 0.5 hPa for p ; ± 3 ° for wd and ± 3 % for ws (CAMPBELL SCIENTIFIC, INC., 2015). For all three net radiometers the uncertainties are 0.5 % for pyranometers as well as for pyrgeometers (KIPP & ZONEN, 2002, 2014).

All values were collected by two CR1000 measurements and a control data logger made by *Campbell Scientific, Inc.* with a one-minute recording interval. In addition to the mobile measurements the experimental design contained permanent measurements of wind with a *Metek* 3-d sonic anemometer USA-1 as well as T_a and RH with a CS215 sensor of *Campbell Scientific, Inc.* at the center of the park. The permanent weather station was mounted on streetlamps at a height of 3.4 m. The 3-D sonic anemometer worked with a sampling rate of 5 Hz while CS215 worked with the same sampling rate

as the mobile devices (2 Hz). Uncertainties are ± 0.4 °C for T_a , ± 2 % for RH and for wd/ws 2 %.

To determine the UTCI (Universal Thermal Climate Index), a thermal index that represents the temperature of a reference environment with the same thermal load, the important determining factor T_{mrt} has to be calculated (see Eq. (2.1)) as (HÖPPE, 1992; MAYER et al., 2008; LEE et al., 2014)

$$T_{mrt} = \sqrt[4]{\frac{S_{str}}{a_l \cdot \sigma}} - 273.2 \quad (2.1)$$

where S_{str} are the mean radiant flux densities of the human body, a_l is the absorption coefficient for short-wave and long-wave radiation and σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$).

According to HÖPPE (1992), Eq. (2.2) is used to determine S_{str} :

$$S_{str} = a_k \sum_{i=1}^6 K_i F_i + a \sum_{i=1}^6 L_i F_i \quad (2.2)$$

where K_i and L_i are, respectively, the short-wave and long-wave radiation flux densities in the six directions ($i = 1, \dots, 6$); F_i is the angular factor; and a_k and a_l are the absorption coefficients for short-wave and long-wave radiation, respectively.

The collected data of the multisensory WXT 520 and the 3-D infrared and solar radiation data are used to calculate T_{mrt} and also UTCI in 10-minute intervals. For the correct calculation of UTCI, the wind speed at a height of 10 m a.g.l. is required. However, measurements of wind speed at 10 m a.g.l. over the whole experimental time at every measurement point of the field campaign cannot easily be provided. For this we used data of ws generated by the permanent weather station in the “Elisenbrunnen” park and scaled these measurements to 10 m a.g.l. assuming a logarithmic wind profile ($z_0 = 0.8$ m). Data from a permanent station (3.4 m a.g.l.) better represent actual 10 m a.g.l. wind speeds at the specific site than using data extrapolated from the mobile weather station (1.1 m a.g.l.).



Figure 3: Mobile weather station with multisensor WXT520 (Vaisala), CNR1 and CNR4 radiometers (Kipp and Zonen) and data logger (Campbell Scientific).

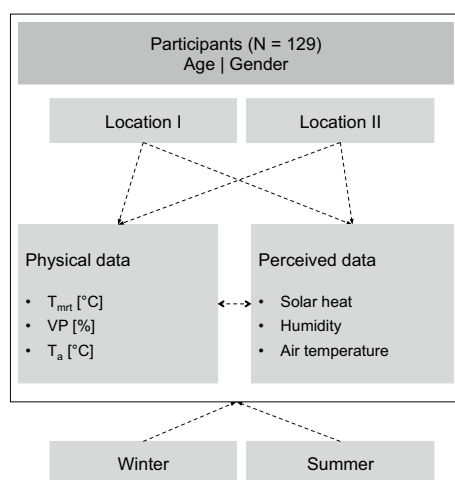


Figure 4: Research model for combined data collection.

Besides human-biometeorological measurements, the overall experimental design includes measurements of particulate matter and acoustics as well. We will not focus on these parts of the interdisciplinary measurement campaigns in this paper since these aspects are covered by PAAS et al. (2016).

2.3 Assessment of the pedestrian perception of thermal comfort: procedure and variables

In face-to-face questionnaire-based interviews with pedestrians, demographic data, as well as individual information about their living situation and social life were assessed. Further, the outdoor time period of every participant was noted in order to relate this to the perception of measured meteorological parameters. Moreover, the perception of the interviewees' own health status, weather sensitivities (e.g. of humid and hot conditions) and meteorological perceptions were included (see Fig. 4). The survey included questions on the rating of the comfort of perceived (air) temperature, solar heat and humidity as well as an estimate regarding the overall weather conditions. The interviews

with pedestrians were always carried out under the same meteorological and boundary conditions as the physical measurements. The sample includes two measurement campaigns with a total $N=138$ pedestrians participating voluntarily. The mean age was 35.4 ($SD = 19.6$) years with an age range from 10 years to 95 years. With regard to gender, 64 (46.7 %) men and 73 (53.3 %) women volunteered to take part in the interviews. For further research, the sample is divided into two locations and separate winter and summer season subsamples.

A total of 62 pedestrians (21 in winter, 41 in summer) were interviewed at the location F. The mean age was 31.4 ($SD = 18.9$) years. In winter, 21 pedestrians with a mean age of 36.1 years (age range from 15–95 years) participated. In summer, 41 pedestrians with a mean age of 29.0 years (age range from 10–73 years) participated.

Altogether, 76 pedestrians (36 in winter, 39 in summer) were interviewed at location B. The mean age was 38.6 ($SD = 19.6$) years, with an age span from 12 to 86 years. In winter, 36 pedestrians with a mean age of 39.8 (age between 15 and 86 years) participated. In summer, 40 pedestrians with a mean age of 37.6 years (age between 12 and 72 years) participated. Two independent variables were studied: the respective city location (1), contrasting the two different sites “Glaskubus” (B) and “Münzbrunnen” (F) (see Chapter 2, Fig. 1, Fig. 2 a) and b)) and the seasons (2), contrasting measurements in winter vs. summer 2014.

Dependent variables referred to both physical measurements as well as the related perceptions. With regard to the perceptual side, we assessed the perceived T_a on a scale (1 = not comfortable at all, 6 = very comfortable), the perceived solar heat (1 = very warm, 6 = very cold) as well as the perceived humidity (1 = not comfortable at all, 6 = very comfortable). In addition, we asked participants to evaluate the overall on-site (weather) comfort as a more holistic impression. Due to the fact that only laypersons were interviewed, we used the term “solar heat” in the questionnaire instead of the meteorological term T_{mrt} . For comparison of the results and for the discussion, we will refer to both terms in the further course of the paper.

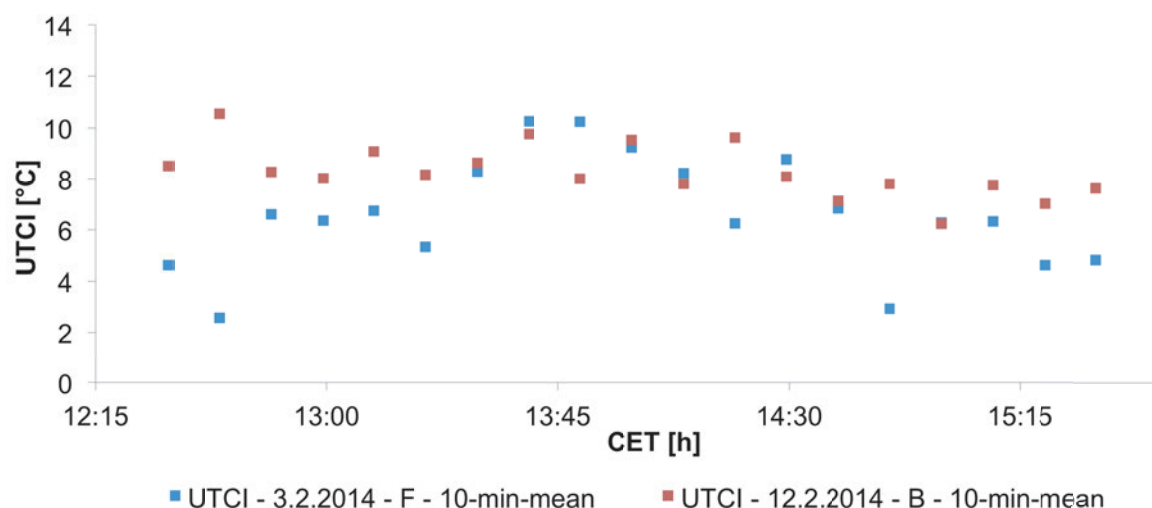


Figure 5a: 10-minute mean values of UTCI for both measurement points F and B for the winter campaign. UTCI (°C) range – stress category: above +46 °C = extreme heat stress; +38 to +46 °C = very strong heat stress; +32 to +38 °C = strong heat stress; +26 to +32 °C = moderate heat stress; +9 to +26 °C = no thermal stress; +9 to 0 °C = slight cold stress; 0 to –13 °C = moderate cold stress; –13 to –27 °C = strong cold stress; –27 to –40 °C = very strong cold stress; below –40 °C = extreme cold stress.

3 Results

3.1 Meteorological boundary conditions

Based on the objective weather type classification scheme of the German Weather Service (BISOLLI and DITTMANN., 2001), meridional and mixed forms of atmospheric circulations characterize the four measurement days in February and July 2014. The synoptic weather regimes with generally south-westerly flow dominated the first half of February 2014. SOZZF (Southeast cyclonic cyclonic wet) on the measurement day February 3rd 2014 led to slightly higher T_a and lower precipitation than normal at this time in the city of Aachen. NWAAT (Northwest anticyclonic anticyclonic dry) caused sustained above-average T_a values on February 12th 2014 which was possibly due to temporary advection of Atlantic air masses. Both measurement days started with clear sky conditions but showed increasing cloudiness of 3/8 and up to 6/8 during the afternoon. Mean values of +6.4 °C and +8.3 °C, respectively, for measurement points F and B were recorded.

The weather type classes SWZAT (Southwest cyclonic anticyclonic dry) and NOAZT (Northeast anticyclonic cyclonic dry) dominated the measurement days July 4th and July 23rd 2014. Some cloudiness was observed during the whole experimental time and increased during the afternoon on July 4th 2014. T_a did not exceed +28 °C. In contrast, NOAZT with its more continental characteristics caused above-average T_a on July 23rd 2014. A maximum T_a of +29.5 °C was reached without any cloud cover during the whole measurement time. Mean values of +27.3 °C and +28.1 °C, respectively, for measurement points F and B were obtained.

3.2 UTCI values in the summer and winter campaigns

For a closer look at physically measured thermal comfort, we calculated 10-minute mean values of UTCI by using 10-minute mean values of T_a , T_{mrt} , VP and ws for both seasons (see Fig. 5a) and 5b)). UTCI values show a slightly similar pattern for both measurement days during the summer and winter campaigns. In winter as well as in summer, location B is characterized by higher values of UTCI in comparison with location F. However, the differences are more obvious in summer (Fig. 5b). While measurement point B shows a minimum UTCI value of +30.6 °C and a maximum of +34.1 °C in summer, minimum (+27.8 °C) and maximum (+30.1 °C) UTCI values are lower for F. In winter, a minimum of +2.6 °C and a maximum of +10.3 °C for F are obtained, while for B a range of +6.2 °C to +11.4 °C was found (Fig. 5a). Over the whole experimental time, mean values of +28.8 °C and +5.9 °C, respectively, for summer and winter at location F, and +32.3 °C and +8.3 °C, respectively, for summer and winter at location B, are calculated.

3.3 Overall effects

Data were statistically analyzed using multivariate analysis variance procedures. The location and seasons were defined as independent variables, and physical measurements as well as perception as dependent variables. We used parametric testing procedures throughout – even for the perception measurements (STEVENS, 2012). This was done in order to detect possible relations between the main variables (location and season) which would not be possible using non-parametric Friedman

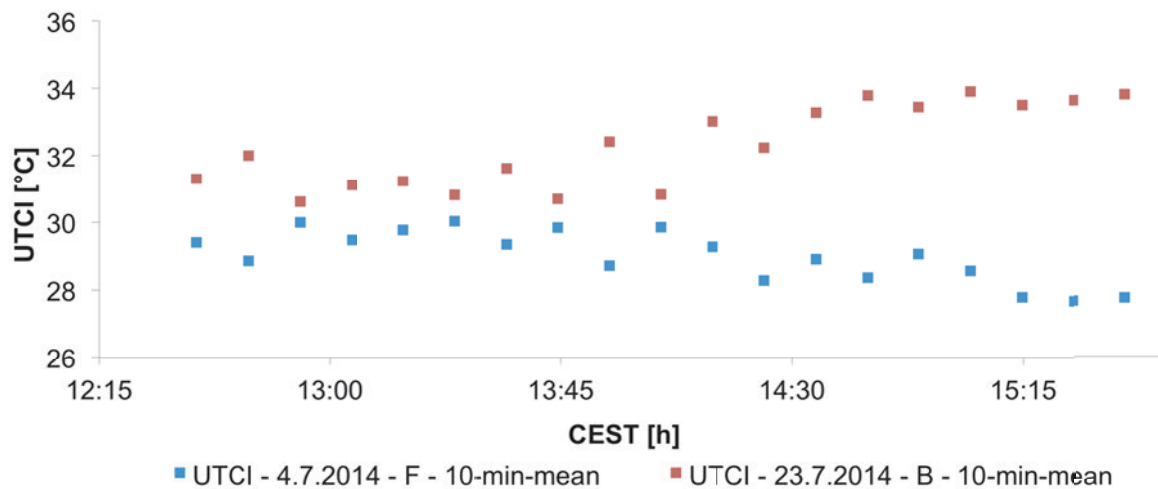


Figure 5b: 10-minute mean values of UTCI for both measurement points F and B for the summer campaign. For UTCI (°C) range – stress category please see Fig. 5a).

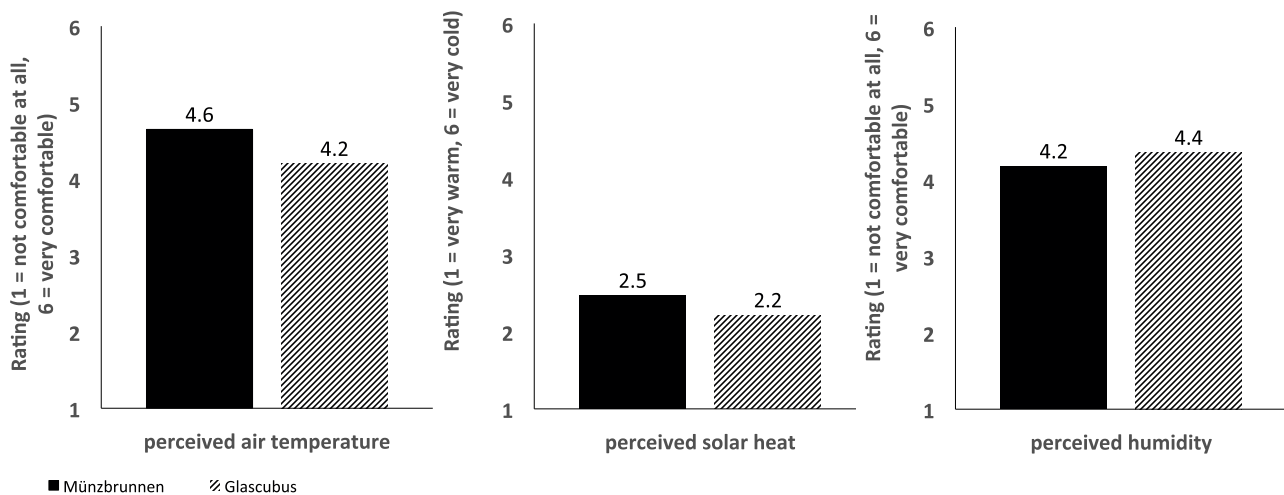


Figure 6: Arithmetic mean ratings of perceived data at different locations (black bar: Münzbrunnen (F), striped bar: Glaskubus (B)).

rank analyses. In order to check potential risks of inadequate scale effects for the significance level, we corroborated in non-parametric procedures whether the same significance pattern is found for parametric and non-parametric procedures. The significance of the omnibus F-Tests were taken from Pillai values. In order to determine correlations between variables, Spearman rank analyses were run. The significance level was set at 5 %. Effects on the less restrictive significance level of 10 % are referred to as marginally significant.

Regarding the omnibus effects, the MANOVA analyses (Multivariate Analysis of Variance) yielded significant main effects of both the on-site location ($F(6, 128) = 5745.6$; $p < 0.000$) and season ($F(6, 128) = 44.4$; $p < 0.000$). Further, the interaction of both variables yielded significant effects ($F(6, 128) = 46.4$; $p < 0.000$). Thus, there were significant differences between measurements in the two city locations as well as differences between winter and summer. In the following, single comparisons and descriptive results are reported in detail.

3.4 Effects of location

Taking both seasons together, there were significant differences in perception of solar heat ($F(1, 136) = 4.8$, $p < 0.05$) and T_a ($F(1, 136) = 3.9$, $p < 0.05$) while humidity was not perceived differently between both sites ($F < 1$; n.s.). In Fig. 6, descriptive outcomes are presented for perception measurements at both locations.

3.5 Effects of seasons

In the following, we concentrate on seasonal differences regarding the physical measurements and pedestrians' perceptions. Naturally, significant differences between summer and winter campaigns were found for T_a ($F(1, 136) = 29506.9$, $p < 0.000$), solar heat ($F(1, 136) = 1074.1$, $p < 0.000$) as well as humidity ($F(1, 136) = 21959.9$, $p < 0.000$). Regarding perceptions, a similar pattern was found for the T_a ($F(1, 136) = 8.4$, $p < 0.005$) and solar heat ($F(1, 136) = 32.3$, $p < 0.000$), while the perceived humidity did not reveal seasonal effects ($F < 1$; not significant) and thus

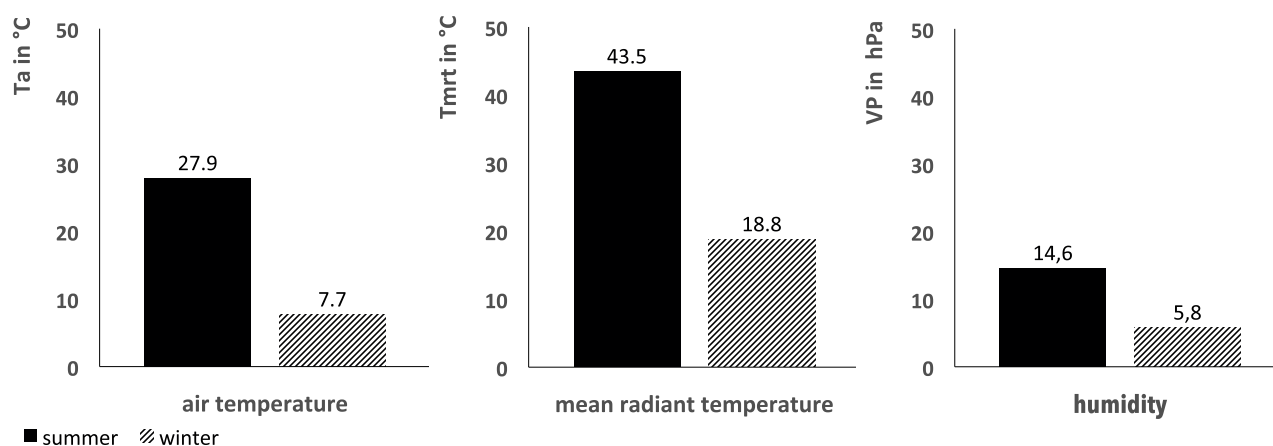


Figure 7: Arithmetic mean ratings of physical data in summer (black bar) and winter (striped bar).

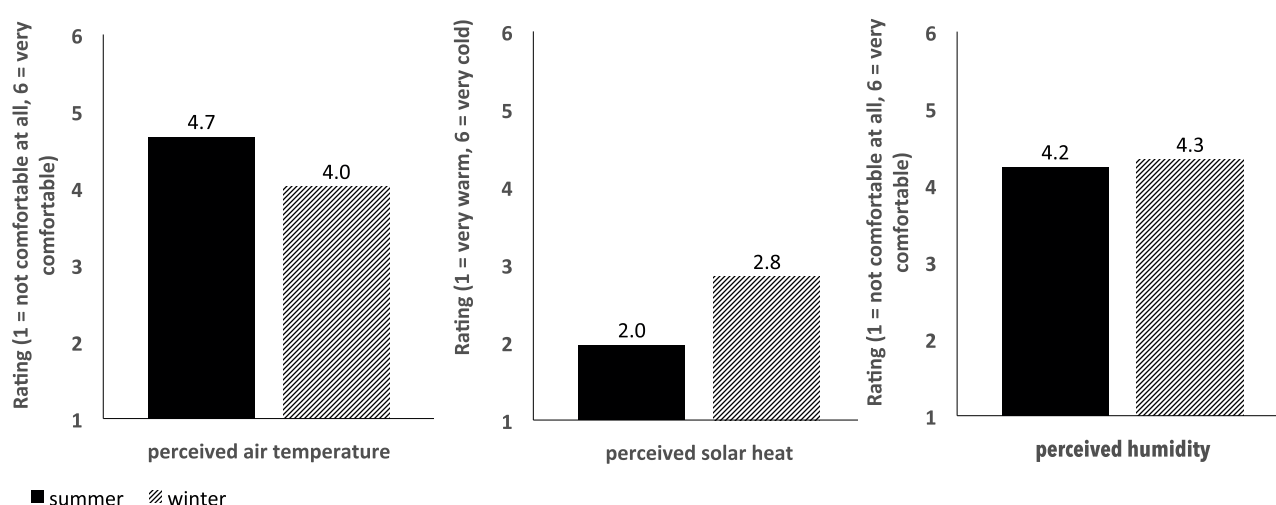


Figure 8: Arithmetic mean ratings of perceived data in summer (black bar) and winter (striped bar).

failed to mirror the factually given seasonal effects for humidity. Descriptive findings are shown in Fig. 7 and 8 and will be evaluated in detail in Section 4.3.

3.6 Relation between psychophysical ratings and perception of weather in general

A final analysis was concerned with the question whether the overall weather perception is impacted by the physical parameters and the perception at all, and if so, which of the parameters forms the overall perception.

First, we analyzed if the perception of weather is affected by the seasons. This was not the case. Participants rated the overall weather conditions in the summer and the winter campaign as equally “comfortable” (summer: $M = 5.3$; $SD = 0.8$; winter $M = 5.3$; $SD = 0.8$). Thus, although atmospheric measurements reflected seasonal effects, this did not have an impact on the perception of the overall weather conditions. As a second step, we ran rank correlation analyses between overall weather ratings and dependent variables in both seasons (see Table 1 and 2).

When looking at the measurements in winter, T_a showed a significant relation to the overall weather perception ($r = -0.28$; $p < 0.05$). Humidity correlated significantly only marginally with the overall weather perception ($r = 0.24$; $p < 0.1$). Further, overall comfort was significantly related to perceived solar heat ($r = 0.27$; $p < 0.5$) as well as to perceived T_a ($r = 0.4$; $p < 0.002$).

In the summer campaign, the resulting patterns were quite different. None of the physical variables significantly affected the weather perception. Only the perceived T_a revealed a significant relation to the overall weather perception ($r = 0.27$; $p < 0.002$). Critically, one could argue that the r values – ranging between 0.25 and 0.4 – are quite low considering that a perfect relation is equal to a value of 1. However, in this context, the discovered correlations are still meaningful from a social science point of view. It was not at all clear if pedestrians have the ability to adequately sense meteorological stressors at all; especially, as it should be taken into account that incidental city visitors and pedestrians are neither trained to evaluate the thermal comfort by rating

Table 1: Psychophysical correlations between physical data and associated perceptions in winter.

*sig. level < 0.05 **sig. level < 0.01	T_a	VP	T_{mrt}	Perception solar heat	Perception T_a	Perception humidity	Perception weather
T_a	1.00	-.49**	-.36**	-.13	-.18	.21	-.28*
VP		1.00	.06	.27*	.03	-.05	.24
T_{mrt}			1.00	-.34**	.11	-.18	.10
Perception solar heat				1.00	.08	-.06	.27*
Perception T_a					1.00	-.39**	.40**
Perception humidity						1.00	.06
Perception weather							1.00

Table 2: Psychophysical correlations between physical data and associated perceptions in summer.

*sig. level < 0.05 **sig. level < 0.01	T_a	VP	T_{mrt}	Perception solar heat	Perception T_a	Perception humidity	Perception weather
T_a	1.00	.08	.76**	-.13	-.22*	.03	.10
VP		1.00	.62**	-.23*	-.13	.01	.00
T_{mrt}			1.00	-.23*	-.16	.09	.10
Perception solar heat				1.00	-.18	.00	.06
Perception T_a					1.00	.30**	.27*
Perception humidity						1.00	.15
Perception weather							1.00

scales nor to separate the thermal comfort ratings from other emotions (general mood, impact of daily activities, psychological states). The small but existing correlations can therefore be taken as a first hint that human perceptions are generally sensitive for those meteorological stressors (at least in the winter season in which the meteorological stressors were more pronounced).

4 Discussion

4.1 Relation between UTCI values and meteorological boundary conditions

UTCI values of both measurement points for summer and winter campaigns strongly depend on the meteorological conditions and the characteristics of both places. In particular, due to the higher values of T_a and T_{mrt} , UTCI values are higher at measurement point B in both seasons (see Fig. 9). Higher T_{mrt} values are caused by two important factors: first, because of the influence of NOAZT, no clouds occurred during the whole period at point B in summer, while slightly more clouds appeared on July 4th 2014 at measurement point F; cloudiness markedly increased after 14.00 h. Second, we assume that besides meteorological conditions, the characterization of both places has a high influence on short and long wave radiation fluxes and thus on T_{mrt} as well. While measurement point F is surrounded by deciduous trees (of heights up to 20 m), measurement point B is an intensively sealed place with only one deciduous tree at some distance away. The shading provided by trees

influenced short and long wave radiation intensively at measurement point F (see Fig. 9). Furthermore, Fig. 9 shows higher values of T_a and VP for B while values of w_s (10 m a.g.l.) were similar at both places. Due to the important influence of T_{mrt} on thermal comfort during summer, UTCI values decreased during the measurement day. In contrast, UTCI values increased during the afternoon on July 23rd 2014. Clear sky conditions led to increased T_a and T_{mrt} (see Fig. 5b, Fig. 9).

Similar meteorological conditions during both measurement days in February 2014 led to a corresponding pattern of UTCI values for both measurement points (see Fig. 5a). We assume that slightly higher values of UTCI for measurement point B are caused by higher T_{mrt} and T_a and slightly lower w_s (10 m a.g.l.) (Fig. 10). In comparison with the summer campaign, the missing foliage of the deciduous trees at measurement point F leads to similar short and long wave radiation fluxes at both places in winter (see Fig. 10). Due to this, it can be concluded that the characteristics of both places show a high influence in both seasons at both places. Whether this is a general pattern or a site specific finding cannot easily be determined at this stage of the analysis.

4.2 Seasonal relation between measured and perceived data

The results of the comparison of seasonal effects on perceived and measured data show different patterns. Significant differences in measured T_a , T_{mrt} and VP occur in summer and winter whereas the perceived data also re-

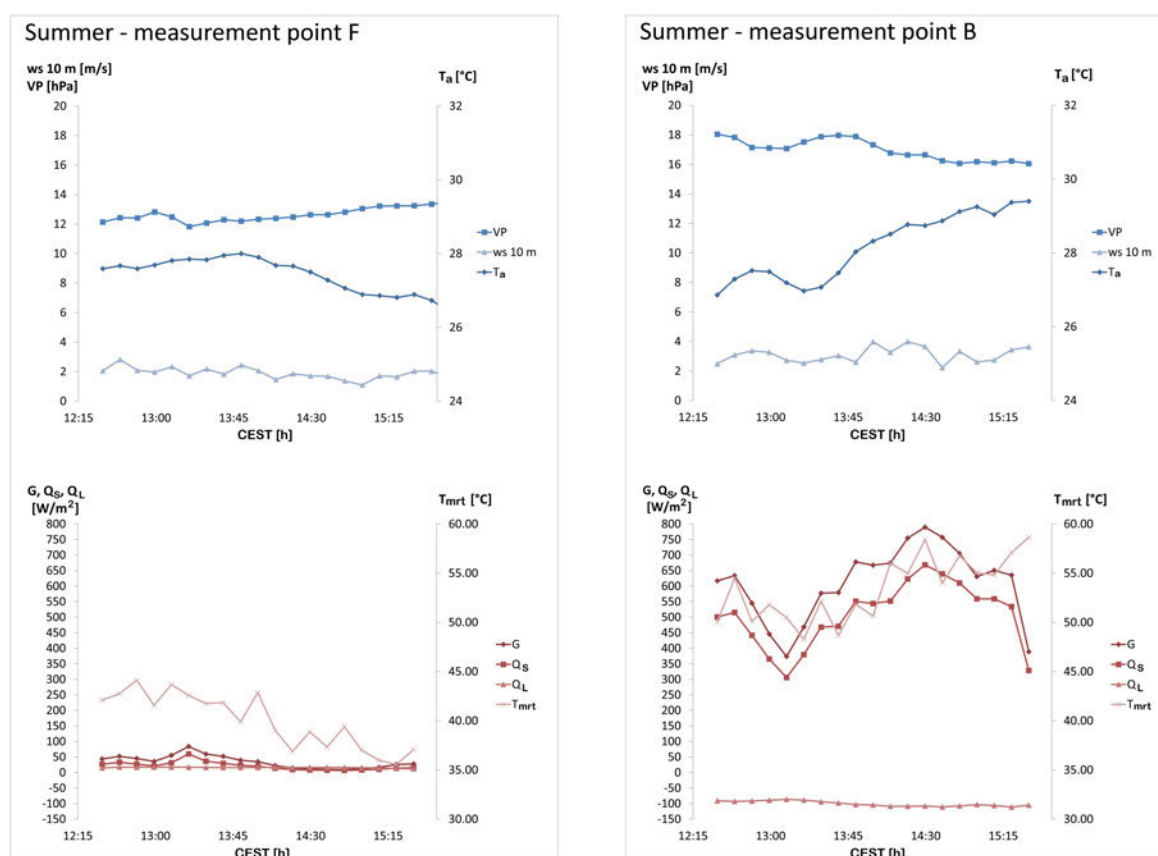


Figure 9: 10-minute mean values of VP, ws (10 m a.g.l.) and T_a (blue levels) as well as of global radiation (G), net shortwave radiation balance (Q_s), net longwave radiation balance (Q_L) and mean radiant Temperature (T_{mrt}) (red levels) for both measurement points F and B for the summer campaign.

vealed a seasonal effect, except for the perceived humidity (see Fig. 6). We have to take into account that, on average, pedestrians assessed T_a as rather comfortable for both summer and winter campaigns. This indicates that values of T_a are not, respectively, high and low enough to generate a perception of discomfort. There is a difference in the perception of T_a between seasons but still both seasons are perceived as comfortable. This leads to the conclusion that differences in “real” T_a on the one hand can be felt but this does not necessarily generate a feeling of discomfort.

Comparing data of measured T_{mrt} and perceived solar heat for both seasons led to the conclusion that the pedestrians are not able to properly assess the intensity of solar heat. Although mean values of T_{mrt} show a difference of 24.7 K between summer and winter campaigns, pedestrians perceived the solar heat both as warm and rather warm. Due to the fact that only laypersons with no professional background in meteorology were interviewed, it can be suggested that they are not able to clearly differentiate between the perception of T_a and solar heat (T_{mrt}). Nevertheless, measured T_a is an important physical factor for the overall weather perception. At both locations and in both seasons, we obtained a high and significant correlation of T_a with the overall weather perception. No significant differences occur between perceived humidity in summer and

winter. Pedestrians perceived both as being rather comfortable. This can be explained by the narrow link between VP and T_a . Based on SCHARLAU (1943), humid-warm conditions with a vapor pressure of 18.8 hPa, corresponding to a dew point temperature of +16.5 °C, are defined as “sultriness” and are perceived as uncomfortable (STEADMAN, 1979). The summer T_a in combination with measured RH are not defined as “sultry” conditions (humid-warm, $VP > 18.8$ hPa). RH should be higher than 50 % for a T_a of +27.9 °C in summer to be defined as a “sultry” condition. Due to this finding, we assume that pedestrians did not perceive conditions as uncomfortable due to a lack of the feeling of “sultriness”.

4.3 On-site relation between measured and perceived data

Pedestrians perceived physical parameters at the same time as measured at both places in both seasons as being similar (see Fig. 7 and 8). In particular, no differences occurred for perceived humidity at all. In comparing results of perceived humidity with results of measured VP, differences can be seen. Pedestrians felt comfortable in both seasons while measured values show a difference (see Fig. 7 and 8). Due to the fact that VP mean values are not unusually high or low for the measurements in both seasons, this result could be expected. Despite the

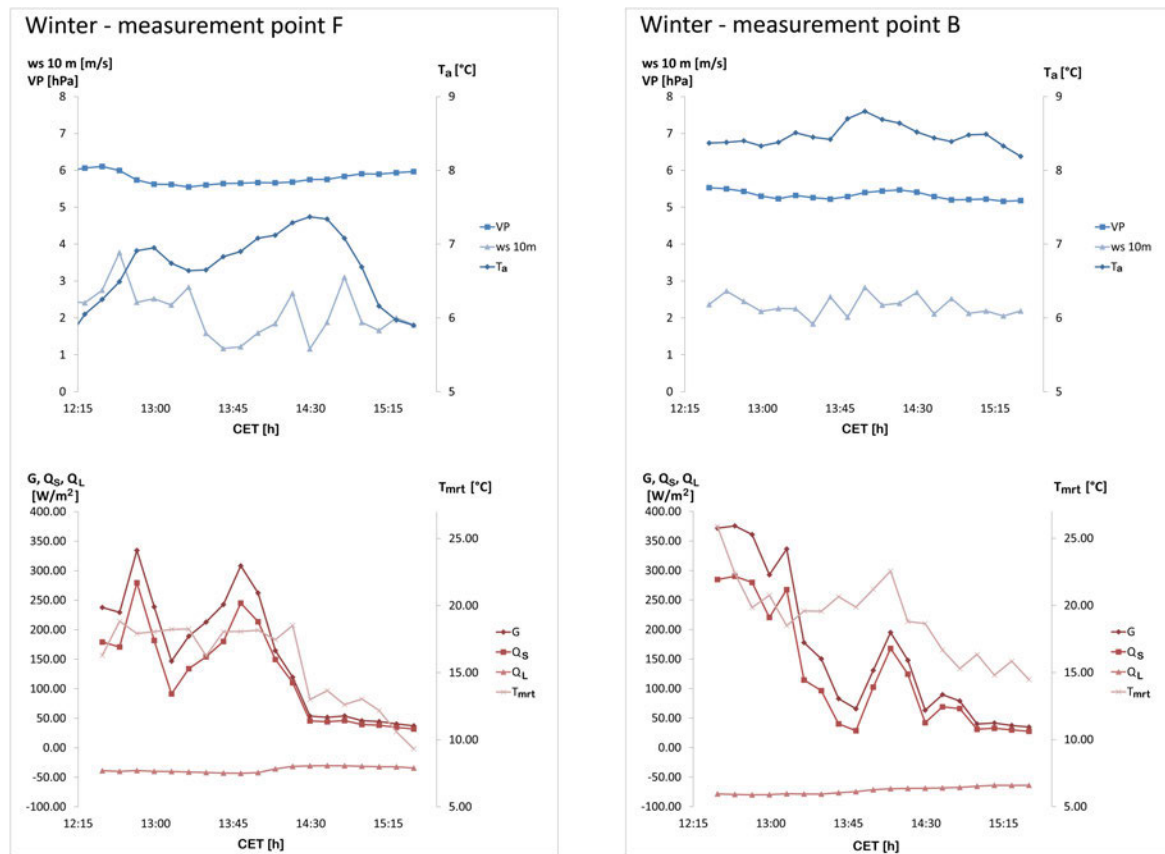


Figure 10: 10-minute mean values of VP, ws (10 m a.g.l.) and T_a (blue levels) as well as of global radiation (G), net shortwave radiation balance (Q_s) and net longwave radiation balance (Q_l) and mean radiant Temperature (T_{mrt}) (red levels) for both measurement points F and B for the winter campaign.

fact that both locations are very different in structure and attributes, pedestrians felt comfortable at these places under the prevailing overall weather conditions. In summer, interviewed pedestrians were able to perceive a difference in solar heat. According to the mean values, pedestrians perceived solar heat hotter at measurement point B than at measurement point F (see Fig. 8). Actually, a large difference of 20.6 K in mean values of T_{mrt} occurred in summer between both measurement days for these locations (F = 33.3 °C; B = 53.9 °C) (see Fig. 7). Although perceived solar heat showed differences for mean values, similar values of measured T_a were perceived as being rather comfortable at both places in summer. Due to this, we assume that pedestrians are more likely to be able to differentiate between the physical factors T_{mrt} and T_a under hot conditions in summer time than during typical winter conditions, which may be related to their clothing in winter. In this case, the characterization and structure of the regarded locations do not seem to have an influence on perception.

5 Conclusion

In this paper, we present an interdisciplinary research design for measuring and analyzing both meteorological and perceived data concerning thermal comfort in

urban public space. Results for two of the five locations at the study site “Elisenbrunnen” in the middle-sized European city of Aachen are presented for a summer and a winter campaign. In addition to taking measurements at the human-biometeorological standard height of 1.1 m a.g.l., we conducted on-site questionnaire-based interviews with pedestrians. UTCI values for both measurement points in the summer and the winter campaign were calculated. We investigated seasonal effects as well as location effects for the parameters T_a , VP and T_{mrt} for a detailed analysis and comparison of both datasets. Although particularly significant differences in measured data occurred during the seasons, as well as between both locations, correlations between measured and perceived data provide marginally significant results. The highest correlations occurred between T_a and the overall perceived weather conditions for both summer and winter campaigns. Therefore, it can be concluded that pedestrians felt comfortable with the overall weather conditions when at the same time their perception of the temperatures was also comfortable or vice versa. Furthermore, we can conclude that the perception of single meteorological stressors tends to be overlapped by the combination of different meteorological factors. Values of UTCI showed the importance of the physical parameter T_{mrt} . Comparisons between summer and winter campaigns for both sites demonstrate the strong

influence of meteorological conditions characterized by changing cloudiness and changes in long- and shortwave radiation fluxes due to the characteristics of the measurement points.

We will extend our study by investigating another middle-sized European city in North-Rhine Westphalia (Münster). The winter campaign was conducted in February 2015 and the summer campaign was run in July and August 2015. One of the objectives will be the further analysis of correlations between measured and perceived thermal comfort. In particular, we will focus on the relation between physical parameters and the perception of comfort or discomfort of overall weather conditions. However, with respect to the limitations of the measurement setup, we will try to eliminate more resulting uncertainties by using larger datasets and to compare measurement data with results of the numerical model ENVI-met. In further studies, we will not only use the UTCI for evaluation of thermal stress but mPET as well, due to the uncertainty of the derived quantity UTCI being influenced by the modeled wind speed at a height of 10 m a.g.l.

Furthermore, our interest is primarily focused on the development of a combined comfort index, which will then combine results of thermal comfort with data of particulate matter and acoustics in public urban places.

Another major research duty regards the specific vulnerability of different persons with respect to their sensitivity to thermal comfort. In this context, the vulnerability of different age or gender groups comes into focus and needs to be examined in greater detail in further analyses.

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